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ON THE SOURCES OF LUMINOSITY IN THE ELECTRIC ARC.

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ON THE SOURCES OF LUMINOSITY IN THE ELECTRIC ARC.*

By Henry Crew and Olin H. Basquin.

Presented by Charles R. Cross, March 9, 1898.

When one considers any actual source of luminous energy, many possible causes of luminosity suggest themselves. In the case of an ordinary tallow candle, we have a considerable development of heat at a temperature high enough to melt platinum, while at the same time hydrocarbons are vaporized, decomposed, and again united with elements of the atmosphere, to form the well known gaseous products of combustion. Is the light of the candle flame immediately due to the high temperature or to the chemical action which is going on? Evidently these chemical processes do not take place except at high temperatures. This fact, however, only makes high temperature a necessary, not a sufficient, condition of luminosity. Kayser and Runge have shown that a large part of the spectrum of the carbon arc is due to the union of carbon and nitrogen,—perhaps to form CN. Runge and Paschen find that an atmosphere of oxygen is almost a *sine qua non* for obtaining the compound line spectrum of S and Se.

In the Plücker tube, in the electric arc, and in the electric spark, we have, beside chemical affinity and high temperature, still another possible cause of luminosity, viz. the electric and magnetic field.

Why does the oscillatory discharge † give the blue spectrum of argon, and the deadbeat discharge the red spectrum? Is the temperature so different in these two cases as to account for the different spectra, or does the rapidity with which the electric potentials vary determine to some extent the *kind* of atomic shock produced? That the atomic motions are affected by a magnetic field is a part of the recent brilliant discovery of Zeeman.‡

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* The following investigation has been made possible through financial aid extended by the Trustees of the Rumford Fund.

† Trowbridge and Richards, Amer. Jour. Sci., Vol. III. pp. 15–20 (1897).

‡ Work of Graham at Berlin shows that the rate of variation of potential in the Geissler tube keeps pace with the variation of luminosity, — as R. W. Wood observed to be the case with temperature.

Of the three processes, thermal, chemical, and electrical, at work in the ordinary electric arc, to which is immediately due the light of the arc? Or is the light partly due to one process and partly due to another? And, if so, what is the character of the radiation due to high temperature alone, what that due to chemical action, and what that immediately due to the electric current?

Some general questions of this character suggested the following experiments. But the one definite question which these experiments were intended to answer may perhaps be more clearly stated in terms of the nomenclature which E. Wiedemann * has employed in his suggestive work on the Mechanics of Luminosity. Using his nomenclature, all sources of luminosity (*Licht-entwicklung*) are either *normal* or *luminescent.* The luminosity of a body is *normal* when it is produced by high temperature *alone,* — i. e. the luminosity of a body is normal when it satisfies the condition of Kirchhoff's Law. Bodies which become luminous through other causes than that of high temperature are said to be *luminescent.* The process of producing light without a corresponding high temperature is called "luminescence." Wiedemann distinguishes six different kinds of luminescence. One or two will serve to illustrate the process. Fluorescence, in which luminosity is brought about by mere illumination, is called *photo-luminescence.* The light produced by breaking lump sugar, or by rapidly unwinding bicycle tape, is an instance of frictional-, or *tribo-luminescence.* The radiation which comes from a slightly heated piece of fluorspar illustrates *thermo-luminescence.*

These and many other instances of luminescence are well known.† But it may be fairly doubted whether "normal luminosity" has ever been experimentally realized.

Dr. Paschen,‡ of Hannover, has recently shown, in the most beautiful and satisfactory manner, that a gas so slightly heated as to preclude the supposition of any chemical change going on within it will emit an invisible spectrum. This spectrum he has determined by means of the bolometer, and has shown it to be a characteristic spectrum. Whatever the inferences which may be drawn from Paschen's experiment, no one, so far as we are aware, has shown that high temperature alone will produce a

* For an excellent résumé of Wiedemann's ideas and terminology, see Winkelmann's article on *Phosphorescenz* in his Handbuch der Physik.

† It is here not to be forgotten that even a most excellent nomenclature, such as Wiedemann's, does not of itself add anything to our understanding of the actual processes named. It is, however, a great aid to clear thinking and clear writing.

‡ Paschen, Wied. Ann., Bd. L. pp. 409–443 (1893).

visible spectrum which is linear or characteristic. The following experiments are an attempt to answer this question, *Is it possible by heat alone to obtain the characteristic visible spectrum of a gas?*

We wish to distinctly avow at the outset that our answer is not so definitive as is to be wished. Having, however, perfected a practical experimental method for maintaining a metallic vapor at an exceedingly high temperature and isolated from electric influenee, — more exactly an electric or magnetic field, — a report upon this part of the work, together with several incidental results, is now submitted.

The method employed to separate the electrical, chemical, and thermal effects — or, more properly, to isolate the thermal effects — is as follows. The process involves three steps: —

(1) The use of an electric arc between chemically pure metallic poles.

(2) The use of this arc in gas which is chemically inert with respect to the electrodes.

(3) The examination of this arc during a very minute interval of time when the current is off the arc, and only after an interval in which the self-induction effects have had time to die down and disappear.

Metallic electrodes are used, since they are freer from impurities and much less complicated, from a chemical standpoint, than carbon.

This arc is then worked in an air-tight metallic box, and this box is flooded with a gas which is chemically inactive towards the electrodes. We have used principally iron poles in hydrogen. This hydrogen is prepared electrolytically by a current varying from 10 to 20 amperes; the small box containing the arc is thus swept out continually by a current of fresh and dry hydrogen amounting to 100 cc. per minute. On the way to the arc this hydrogen is passed successively through two drying tubes of strong sulphuric acid and phosphoric anhydride.

It is not to be forgotten, however, that, while iron and hydrogen are inactive with respect to each other at ordinary temperatures, the laws of high-temperature chemistry and low-temperature chemistry are radically different, so that there is always the possibility of some unknown chemical action at the high temperature of the electric arc. The arc was viewed through a glass window in one wall of the air-tight hood.

To exclude the electric current for an instant and examine the hot metallic vapor immediately afterwards, the following device was used.

An alternating dynamo of 100 volts was employed to feed the arc. But in series with the armature, and on the same shaft with the armature, were placed two interrupters, which cut out either all the positive or all the negative parts of the alternating current.

In either case, the current is broken at the instant represented by the current-curve crossing the axis of X. The intervals $A'B'$, $A''B''$, etc. in Figure 1, are the intervals during which the current is heating the arc; while the intervening intervals $B'A''$, $B''A'''$, etc., are the intervals during which the visual or photographic examination of the arc is made.

FIGURE 1.

The interrupting disks, placed in circuit one on each side of the arc, are made of rather heavy brass rings, 30 cm. in diameter, and insulated from the shaft on which they rotate. Into the faces of these brass rings are set two slate sectors, each 45° in length, as represented in Figure 2.

A pair of large brush holders is centred on the same shaft with the interrupters. Each holder carries two brushes, which bear on the interrupter at points 90° apart. Since the dynamo is an eight-pole machine, it is evident that the current will be "on" half the time and "off" half the time, both sides of the circuit being opened and closed alternately at the end of each 45° of rotation.

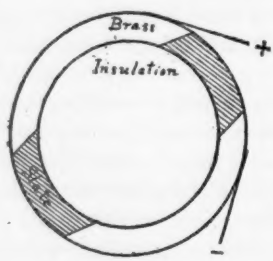

FIGURE 2.

The brush holders are, of course, adjustable so that they may be set at a position of minimum sparking. But one defect of this method of interruption is that the brushes must have a finite thickness, and hence can never cross the boundary between brass and slate without *some* sparking. Not only so, but as the phase of the current changes with load to a slight extent, the angular adjustment of the brushes can never remain perfect. To reduce these changes of phase to a minimum the terminals of the dynamo were kept on a closed circuit all the while, the poles of the

machine being shunted through a bank of incandescent lamps. So that the arrangement of the complete circuit was as in Figure 3.

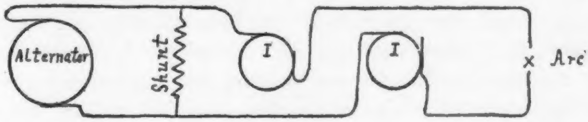

FIGURE 3.

Still a third source of sparking lies in the slight inaccuracy of dimensions in the interrupter rings as they come from the mechanician. While the spark which thus remains is larger than we should like, it has not at all injured the sharp line of contact between the brass and the slate portions of the interrupter; and its only effect on the arc, so far as we are able to observe, is slightly to delay the break of the current, by furnishing, at the point of interruption, a bridge of metallic vapor.

So far as the method of experiment is concerned, it only remains to state how the intervals during which the current was off were employed to observe the arc. For this purpose a steel disk 71 cm. in diameter was placed on the end of the same shaft which carried the armature and the interrupters. Near the periphery of this disk were cut four openings, as indicated in Figure 4.

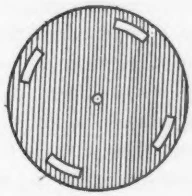

FIGURE 4.

These openings were provided with shutters, so that their angular width could be varied from 0° to 26°. Behind this disk (and at the same distance from the shaft as the centre of one of these openings) was placed the arc. The line of vision was parallel to the axis of the shaft. The steel disk was so adjusted, in azimuth, on the shaft that the light of the arc was excluded from the eye until the brush was $9\frac{1}{2}°$ on the slate sector. In like manner, the light was cut off from the eye of the observer $9\frac{1}{2}°$ before either brush had passed off the slate sector of the interrupter. The effective diameter of this steel disk was 59 cm. The disk was driven

by a gas engine at 1,700 revolutions per minute, corresponding to a rim speed of over 50 meters per second.

Under these circumstances, no light was admitted to the eye until $\frac{1}{1000}$ of a second after the current had been cut off. And the line of vision was again interrupted $\frac{1}{1000}$ of a second before the arc was again made. In later experiments, the aperture was stopped down to $\frac{1}{1000}$ second in time; but the maximum time for which the arc was visible was $\frac{3}{1000}$ of a second.

At this point the question naturally arises as to whether the self-induction of the circuit can prolong the purely electrical effects, whatever they may be, through an interval of time as great as $\frac{1}{1000}$ of a second.

The form of the circuit is practically that of two parallel copper wires, each 180 cm. long and separated by a distance of 30 cm. If the current be not oscillatory [?] we may fairly assume that its time constant will lie somewhere between that of a circle of wire (having the same diameter as the wire actually used and enclosing the same area as the circuit actually used) and a 180 cm. section of two parallel wires 30 cm. apart and open at *both* ends.

Computing the time-constants for these two cases, we have* for the parallel wires,

$$L = 2\mu \log_e \frac{b^2}{a_1 a_2} + \tfrac{1}{2}(\mu_1 + \mu_2);$$

where $\left\{\begin{array}{l} L \;= \text{self-induction of unit length.} \\ \mu \;= \text{permeability of medium between wires.} \\ \mu_1 = \text{permeability of one wire.} \\ \mu_2 = \text{permeability of other wire.} \\ a_1 = \text{radius of one wire.} \\ a_2 = \text{radius of other wire.} \\ b \;= \text{shortest distance between the axes of the wires.} \end{array}\right.$

Here

$$\mu = \mu_1 = \mu_2 = 1,\ a_1 = a_2 = 0.1 \text{ cm., and } b = 30 \text{ cm.}$$

Hence,

$$L = 4 \log_e 300 + 1 = (4 \times 2.477 \times 2.30) + 1 = 23.$$

Inductance of circuit 180 cm. long = $23 \times 180 = 4140$. C. G. S.

Resistance of 360 cm. of this wire = 0.02 ohms approx. = 2×10^7 C. G. S.

$$\therefore \text{Time-constant} = \frac{4140}{20000000} < \frac{1}{4000} \text{ sec.}$$

* Gray, Absolute Measurements, Vol. II. Pt. I. p. 293.

If we consider the arc itself as having appreciable resistance, this time-constant is still smaller. If, on the other hand, we consider the actual circuit as equivalent to a circular one *of equal area*, the radius of this circular circuit will be 45 cm.

Its self-induction * will be

$$L = 4\,\pi\,a\left(\log\frac{a}{R} - 2\right),$$

where a is the radius of the circuit, 45 cm., and R is the "geometric mean distance" of the cross section of the wire from itself, defined by the following equation:

$$\log R = \log r - \tfrac{1}{4},$$

where $r =$ radius of cross section of wire.

Here $r = 0.1$ cm. Hence $R = 0.7788\,r = 0.0778$.

Hence

$$L = 12 \times 45\,[\log 45 - \log 0.07788 - 2]$$
$$= 12 \times 45 \times 2.3\,[1.653 - \bar{2}.891 - 2] = 12 \times 45 \times 4.35 = 2340.$$
$$\therefore\quad \frac{L}{R} = \frac{2340}{2 \times 10^7} = \frac{1}{10000}\text{ sec., approx.}$$

In each of these cases it is to be borne in mind that the initial current, the decay of which we are studying, is but a minute fraction of the strength of the alternating current operating the arc.

The conclusion of the whole matter is, that there is no evidence, either from an examination of the arc or from electrical theory, that the current in this short isolated strip persists for a length of time comparable to one thousandth of a second.

In fact, the instant the brushes of the interrupters have passed on to the slate sectors, the whole circuit consists simply of two short pieces of thick copper wire with one pair of terminals nearly in contact, the other widely separated by a piece of slate carefully selected with reference to its high insulating power.

Further evidence will be furnished, by experiments to be described later, for thinking that the phenomena which appear when the current is off are quite independent of the self-induction of the circuit.

It need scarce be added, that in place of the eye of the observer, in front of the steel disk, may be substituted the spectrograph or the photographic camera. In this case, both arc and spectrograph are placed on a large table with a long hole cut into the top of it so as to clear the

* Gray, Absolute Measurements, Vol. II. Pt. I. p. 308, Eq. (119').

occulting screen, the arc on one side the screen, the camera on the other. Rubber corks, placed in the legs of this table, free it from serious vibration even in the neighborhood of high speed shafting.

The spectrograph employed was made by Bartel of Göttingen. The collimator and objective had each an aperture of $1\frac{1}{2}$ inches. The dispersion piece was a 2″ Rowland grating, 14,438 lines to the inch.

For the identification of the hydrogen lines which always made their appearance when an atmosphere of hydrogen was employed, this same instrument was used visually, a spectrum tube of hydrogen furnishing the comparison spectrum. Ordinarily, for the visual examination of the arc, a small direct-vision instrument was employed. For the examination of the fluorescent light, mentioned at the end of this paper, a Browning single prism instrument was tried with wide slit; also the direct-vision instrument; but the source was entirely too faint to produce a visible spectrum. The conclusions there stated, viz. that the spectrum of this fluorescent light is not characteristic, rest merely upon the fact that this light presents to the eye the same appearance for all the metals tried, viz. a luminosity resembling fluorescent light in general; and further, upon the probability that, if this spectrum were concentrated in lines, some of them might be visible in the spectroscopes employed.

For the purpose of determining the manner in which the rise and fall of the arc occurs when the circuit is made and broken, respectively, it is only necessary to move the eye either to the one side or the other so as to catch the light of the arc a little earlier or a little later than the instant of break.

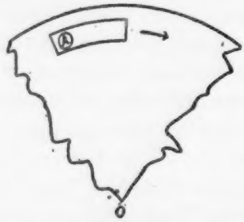

FIGURE 5.

Let A represent the arc as seen through an opening in the disk by an eye looking in a direction parallel to the shaft of the dynamo. Then by moving the head to the right one will see the arc in a later phase; since the line of vision above and parallel to the shaft will not be intercepted until a later instant. Hence, by moving the arc and head together slowly

from a position just over the shaft to one on the right, one sees the rise of the current. In like manner, motion of the arc and head from a position just over the axis to one on the left will give the observer a chance to see the decay of the current.

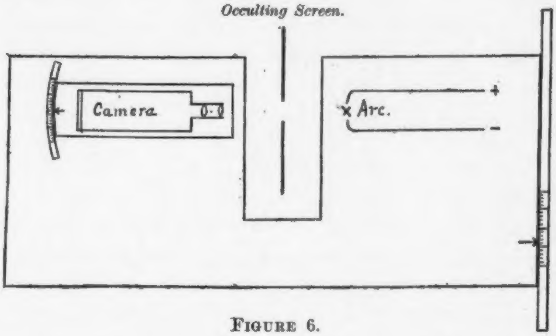

FIGURE 6.

For the purpose of photographing the arc in various stages of its rise and decay, we rigidly connected the arc and camera to a sliding table top; for each 5 mm. displacement of this table top the phase at which the arc is first seen or last seen is changed by $\frac{1}{10000}$ second. On this table the camera was so arranged as to rotate about a vertical axis

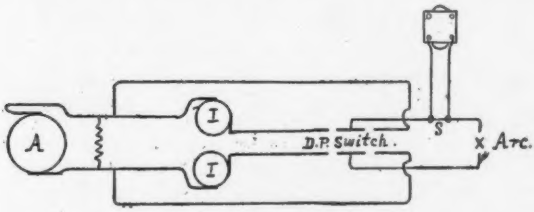

FIGURE 7.

passing through the optical centre of the lens. In this manner were photographed, on one plate, several series showing the arc in successive phases, differing by one or two ten-thousandths of a second.

I. THE INTERMITTENT ARC.

A double pole switch convenient to the observer enabled one to operate the arc either with the ordinary alternate current or by the alternate

current which had passed through the interrupters. This latter we shall call, for convenience, the "intermittent" current. A voltage of approximately 70 was ordinarily used.

To the naked eye the appearance of these two arcs, the alternate and the intermittent, is the same except in size. But they present the following striking difference to an observer on the side of the occulting disk next the arc. Through the openings in the occulting disk, a lens projects an image of the arc upon a white screen on the side of the disk *away* from the arc. This screen is visible through the disk all the while. The alternating arc is visible upon the occulting disk and upon the screen at all times; but the intermittent arc is seen only on the occulting disk. The image appears to hang in mid-air, and although the white screen is seen with perfect distinctness the intermittent arc which is projected upon it bears little or no resemblance to that projected upon the occulting disk. The light which reaches the screen (that is, the light which penetrates the occulting disk) is that which has persisted after the current has been cut off. Such an occulting disk in connection with the interrupters, then, forms a most convenient means of separating radiations according to their length of life after the exciting current has been cut off.

II. The Persistent Luminosity of the Arc.

In the case of the iron arc, we have measured the duration of the luminosity after the current has been cut off and find that with a voltage ranging from 70 to 80 and a current varying from 10 to 20 amperes the life of the white luminous cloud that floats above the junction of the electrodes covers a period of from two to five thousandths of a second after the disappearance of the current.

By the use of the sliding table top we have photographed the rise and decay of the arc.

In Figure 8 are reproduced three series of seven photographs each. All of the series are taken under the same conditions. Each series, beginning at the left and going to the right, depicts the decay of the current. The first of the series represents the arc as it appeared $\frac{2}{10000}$ of a second *before* the current was interrupted. The last photograph, the one at the extreme right, represents the arc as it appeared $\frac{4}{10000}$ of a second *after* the current was interrupted. All the photographs were taken at equal intervals of $\frac{1}{10000}$ of a second. It is evident, therefore, that the third photograph was taken just as the brush of the interrupter passed on to the slate sector. It will be observed that the arc proper (which is

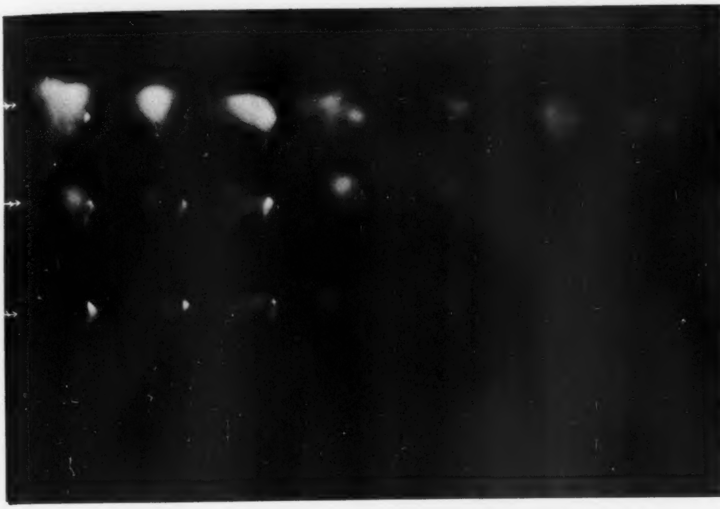

FIGURE 8. Reduced one half.

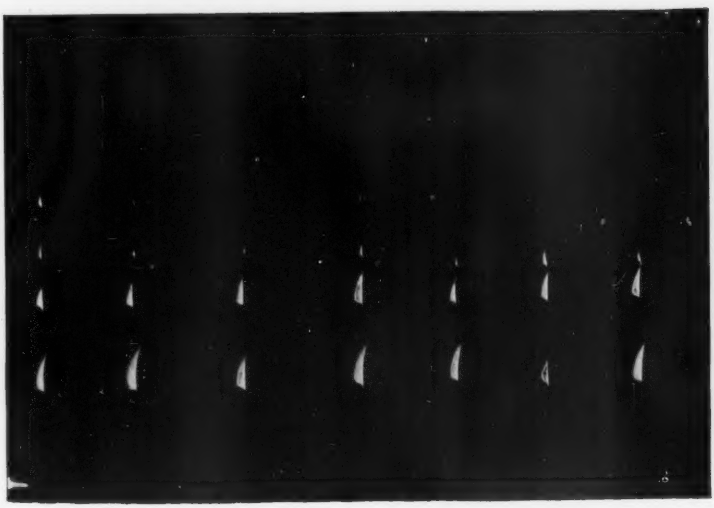

FIGURE 9. Reduced one half.

represented by the bright triangular area in the first three photographs of each series) persists for about $\frac{1}{10000}$ second after the brush has passed on to the slate sector. But what remains longest of all is the detached white cloud which persists from eight to ten times the whole interval covered by one of these series of photographs. Each of the twenty-one photographs is a composite of about 200 single exposures, the whole 200 exposures occupying just two seconds.

In Figure 9 are reproduced seven series of four photographs, each series representing the *rise* or growth of the arc. Each series is arranged in a vertical column. The first photograph of the series, the one at the top, was taken $\frac{1}{10000}$ second after the circuit was closed, the next three are made at immediately succeeding intervals of $\frac{1}{5000}$ second. These are also composites of about 200 exposures, the whole set of 200 occupying but two seconds. It will here be seen that the luminous cloud which was so slow in disappearing is also tardy in making its reappearance.

In the third and seventh series no arc appears even after $\frac{1}{10000}$ second. A bouncing of the brush might explain this for a single exposure. But it is not so easily explained in a composite of 200 exposures.

In Figure 10 are reproduced six typical photographs of the detached cloud as it appears at the middle of the interval during which the current is off the arc. The bright point to the right is the red-hot iron electrode. The exposure is two seconds, aperture $\frac{1}{6}$ the focal length — "Carbutt A" plates — unit magnification. These six photographs are all taken in the same phase. It will be observed that no trace of the arc remains, but that the luminous cloud is as bright as red-hot, perhaps molten iron.

Whether or not this after-luminosity is a phenomenon corresponding to the "flame" which accompanies the carbon arc remains to be decided.

III. Effect of Self-Induction.

In order to discover whether self-induction had anything to do with the persistence of this after-luminosity, the primary of a 25-light transformer was put in series with the arc, the circuit being arranged as indicated in Figure 7, so that the switch S could throw in or cut out the transformer without interrupting the arc. No effect was certainly observable either by the eye or on the photographs, although the time-constant of the circuit must have been enormously increased.

So far as the evidence thus far presented is concerned, this persisting luminosity appears to be what Wiedemann would call chemi-luminescence, or thermo-luminescence, and not electro-luminescence.

IV. Intermittent Iron Arc in Oxygen and Hydrogen.

In an atmosphere of oxygen, this persisting luminosity is very much increased; while, when the hood of the arc is filled with hydrogen, the luminosity is very much decreased. In hydrogen, the light is also very red and yields the H_{α} and B_{β} lines (C and F of Fraunhofer) as already observed by Liveing and Dewar.*

After the arc has been working in oxygen for a few minutes the whole interior of the hood is lined with a light brown deposit, which is evidently iron oxide.

In hydrogen, on the contrary, the iron electrodes in the parts that become hot present a bright metallic surface, which shows the reducing effect of the hydrogen on the iron *oxide;* but there is no evidence of any chemical action between the iron and the hydrogen.

So far as the brilliant luminosity of the iron arc *in oxygen* is concerned, it is evident that it might be due *either* to the oxidation of the iron *or* to the increased heat produced by this oxidation.

In the case of hydrogen, we should say that chemi-luminescence were ruled out were it not for the fact that in the hydrogen flame, which burns as it escapes from the chamber surrounding the arc, there is always a small white core, a flame in color not unlike that of ordinary illuminating gas or acetylene.

Since the hood was thoroughly cleansed from all forms of oil and grease, and since the bearings were run dry in clean asbestos packing, the only source of carbon would appear to be that which we know to be present as an impurity in the iron electrodes.

That this carbon impurity *is* the true source of the white flame is made highly probable by the fact that "chemically pure" zinc and magnesium poles gives no trace of it, the carbon in these being very much less than in the impure iron employed.

V. Intermittent Arc of Pure Zinc and Magnesium in Hydrogen.

To realize the conditions indicated in this caption may be considered the chief object of this experiment. For with a large current of fresh, dry, and pure hydrogen sweeping out the hood of the arc, we may feel fairly certain that oxidation is ruled out, except at the very start. Any of the original air in the hood still remaining, its oxygen would be

* Liveing and Dewar, Proc. Roy. Soc., Vol. XXXV. p. 74; also Vol. XXX. p. 152.

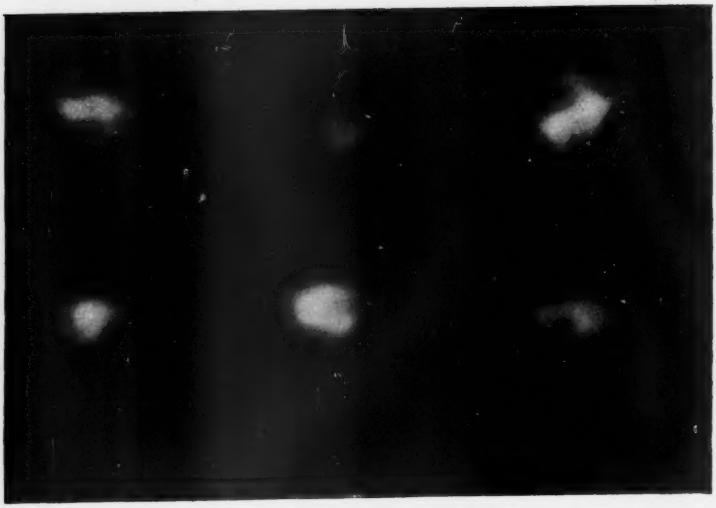

FIGURE 10. Reduced one half.

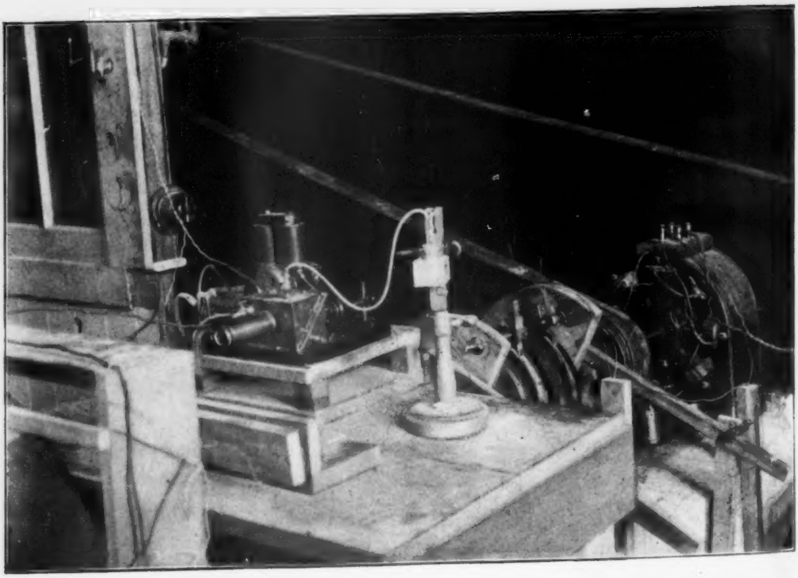

FIGURE 11.

very quickly used up after the arc was once started. Indeed, we always find a slight whitish deposit of oxide on the electrodes of Zn and Mg when the arc is started too early.

And with pure zinc and magnesium poles we may feel fairly certain that no ordinary or well known chemical action is going on. Observations were taken only after the stream of hydrogen had been running through the hood for half an hour. After passing two tubes of phosphoric anhydride, it would seem wellnigh impossible that any moisture should remain in the hydrogen. Figure 11 shows the hooded arc in position.

Under these conditions, neither the arc nor the luminous cloud above the arc is to be seen. Though once in a long while a bit of yellow cloud flashes out for an instant. We have not been able satisfactorily to account for this.

The only light that remains, aside from that emitted by the red-hot electrode, is a sort of blue haze, — a blue glow, that fills the whole hood, and is there all the time. This light appears to be exactly the same for all three metals, iron, zinc, and magnesium. It is too diffused and faint to be easily examined in the spectroscope. Is this possibly a phosphorescence of hydrogen, or of the finely abraded particles of metal?

In reply then, to the main question, viz. can the characteristic spectra of the metals be produced by heat alone, we can only say that on heating metallic vapors to the temperature of the electric arc we are unable to discover any characteristic spectrum after an interval of one thousandth of a second.

The form of electrode used by us is, however, very favorable to the rapid cooling of the metallic vapor; and we hope, therefore, soon to try another form, already suggested by one of us, such that the heat will be less rapidly diffused.

Northwestern University, Evanston, Ill.,
February 8, 1898.